SNOW DRIFTING ON ALASKA'S ARCTIC SLOPE, AS MEASURED AT ATKASOOK ON THE MEADE RIVER

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ABSTRACT

The winter snow on the Arctic Slope of Alaska lasts for nine months each year. The Weather Service records have underestimated its quantity by a factor of 3 because of problems inherent in the measuring technique, which consists of using standard (and generally unshielded) 8 inch precipitation gauges. These gauges are known to record less than the true amounts in windy regions, especially when the precipitation comes in the form of snow. The summer rain which amounts to about 20% of the total precipitation is also underestimated by a factor of 1.1. The snow distributed over the tundra represents about half of the amount precipitated. The other half blows away and is largely concentrated in drifts. The snow on the tundra has been measured near Barrow and at eight other locations on the Arctic Slope since 1961. Part of the total flux of drifting snow is lost by sublimation, and its quantity remains to be determined; but the part which is deposited in drifts has been measured for seventeen years in natural "drift traps" formed by the banks of the Meade River near Atkasook. The average annual flux values which resulted in deposited drifts between 1962 and 1979, expressed as metric tons of water equivalent per meter width normal to the winds, are 70 from the east winds and 30 from the west winds. The average transport distance for blowing snow is on the order of 2.5 km. It may go as high as 10 km.

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INTRODUCTION

The basic purpose of this study is to improve our knowledge about snow drifting on the Arctic Slope of Alaska. In order to do this it has been necessary to examine existing knowledge about the precipitation which comes in the form of snow on the Arctic Slope. The best data available are the records from U.S. Weather Bureau stations at Barrow and Barter Island. However, it has been known for a long time that these data systematically underestimate the true precipitation, because of problems inherent in the measuring techniques.

Measuring precipitation in a wind-swept region where the total quantity is small, and nearly 80% comes as snow, is a complex problem. In general, the need for hydrologic information on the amount of water stored in the snow, and the rate at which this water is discharged, gave birth to the field of snow surveying in the Western U.S. (Church, 1942). However, snow surveys present special difficulties in tundra areas because of the thin snow pack and irregularities produced by extreme snow drifting. The snow on the tundra varies in thickness from 10 to 40 cm, with occasional bare patches and local places with deep drifts. Along the sea coast near Barrow drifts are more than 4 m deep and drifts on the banks of large rivers, such as the Meade River, are often several kilometers long, up to 20 m wide and 10 m deep; they may contain from 20 to over 100 metric tons of water equivalent per meter of length along the bank. Therefore, in addition to determining the total amount of precipitation, we need to know what fraction comes as snow and how this is redistributed by wind during and after deposition.

During the 1974-75 winter a joint research project on windblown snow of the Arctic Slope was planned by members of the Geophysical

Institute, University of Alaska and the Rocky Mountain Forest and Range Experiment Station of the U.S. Forest Service. The plan was to combine methods used in the windblown regions of Wyoming (Rechard and Larson, 1971; Tabler and Schmidt, 1973; Tabler, 1975), with those used on the Arctic Slope of Alaska. This research began in September, 1975 at Barrow and Meade River; the Alaskan Arctic Gas Study Company encouraged its extension into the eastern part of the Arctic Slope.

Before discussing the wind-blown snow of the Arctic Slope it is useful to put it in perspective by briefly considering the Alaskan snow cover in general.

ALASKAN SNOW COVER

Snow forms a thin veneer on the earth's surface over most of Alaska for 1/2 to 3/4 of the year. The physical properties of this snow layer and the physical processes which occur in, above, and below it are important and fascinating. The Alaskan snow differs from the hydrologically important mountainous snow of the western United States in that its temperatures are lower, steeper temperature gradients occur in it, and there is less of it per unit area; however, it lasts longer and enters more directly into human activity as snow itself rather than serving primarily as a cold storage water reservoir. This is of course especially true of snow which falls in glacier basins and enters into the complex glacier-hydrology system. Some of it may appear as runoff during the same year it was deposited, but much of it becomes locked in the glacier system for many years before it appears as runoff.

Although Alaska is famous for its glaciers which cover an area of

73,360 km^2, and has a large amount of perennial snow-cover, it is especially well suited for the study of seasonal snow cover. Indeed, Alaska's glaciers, extensive as they are, cover only 5% of the total area--all of which is subjected to seasonal snow. Alaska is virtually a made-to-order snow laboratory because it contains maritime, extreme continental, and Arctic climatic zones in proximity. Striking differences exist in the snow cover from one climatic zone to the next. This fortuitous situation is the result of two sharply defined climatic boundaries which cross Alaska:

(1) The Alaskan coastal ranges separate the north Pacific maritime climate from a severe continental climate.

(2) The Brooks Range separates the interior continental climate from the Arctic polar basin climate.

The two boundaries give three major climatic zones, each of which contains its own characteristic snow cover. Pruitt (1970) distinguished two primary North American snow types, "tundra snow" and "taiga snow", which are widespread in Canada and Alaska. To these we will add "maritime snow" as a third type (Benson, 1967, 1969), and define the climatic zones and their snow types as follows:

(1) Arctic. The Arctic Slope north of the Brooks Range has the climate of the Arctic polar basin (Conover, 1960). Its precipitation comes from cyclonic disturbances moving eastward from the Bering Sea or from along the Siberian Arctic coast. About 65 to 80% of it comes as snow, the snow cover lasts for nine months and is wind-packed, dry, and sastrugi-sculptured. Following Pruitt (1970) we shall refer to this snow as Tundra snow.

(2) Interior. The interior, between the Brooks and Alaska Ranges suffers an extreme continental climate. Most of its precipitation is from cyclonic disturbances which move eastward from the Bering Sea. The total amount is only about 300 mm, one third of this comes as snow, which lasts for slightly more than 6 months. Its most notable physical characteristic is the low-density, loosely consolidated, depth hoar which makes up most of the snowpack in the lowland brush forest areas. Following Pruitt (1970) we shall refer to this snow as Taiga snow.

(3) Maritime. The coastal mountains and lowlands of southeastern and southcentral Alaska receive heavy precipitation from Pacific cyclonic disturbances which move through the Gulf of Alaska. The maritime snow pack is thick, often exceeding 5 m and sometimes exceeding 10 m; it may be wet, especially at low altitudes. Snow temperatures are significantly higher than in tundra or taiga snow. It is common along the Pacific rim northward from Japan and California. We shall refer to this snow as Maritime snow.

(4) Transitional. In addition to these three major climatic types, there is a fourth zone which lies south of the Alaska Range and is transitional between the Interior and Maritime zones. It is called the Transitional zone. Climatic conditions alternate between continental and maritime. In the interior this transitional zone also becomes apparent as one progresses westward toward the Bering Sea, especially west of Koyukuk (about 158°W) on the Yukon-Kuskokwim delta. Here, the temperatures and winds are higher than farther

east and the climate becomes more maritime; many of the snowstorms are mixed with rain and the snow cover is characterized by significant amounts of icing with depth hoar at the bottom. The snow cover is transitional between the three named types but no special name will be applied to it.

THE TUNDRA SNOW OF THE ARCTIC SLOPE

Aside from perennial snow in mountainous areas, the snow cover lasts longest on the north slope of the Brooks Range. For three quarters of each year, the entire Arctic Slope, from the foothills across the tundra to the Arctic Ocean, is covered with dry, wind-packed snow. This tundra snow has several distinct features, and research on it emphasizes the common ground which exists between studies of seasonal and perennial snow cover. It forms a wind-swept, sastrugi surface which strongly resembles the year-round surfaces of the Greenland and Antarctic ice sheets, or the winter snow surface of the adjacent Arctic Ocean.

The similarity between tundra snow and snow on the polar ice sheets does not stop at the surface. Indeed, the structure of the entire tundra snowpack (thin as it may be) resembles the top annual stratigraphic unit of the perennial dry-snow facies of the Greenland or Antarctic Ice Sheets; it consists of a hard, high-density, wind-packed layer, overlying a coarse, low-density, depth hoar layer. Although there is considerable variability in the stratigraphy of this snow, one can generally describe it by referring to only four major varieties of snow. In approximate order from top to bottom in the snowpack these are:

Snow type	Range of Grain Size (mm)	Range of Density ($g\ cm^{-3}$)* (or $t\ m^{-3}$)
1. Fresh new snow, variable crystal forms	0.5 to 1.0 sometimes < 0.5	0.15 to 0.20
2. Wind slab, hard, fine-grained	0.5 to 1.0	0.35 to 0.45
3. Medium grained snow	1 to 2	0.20 to 0.35
4. Depth hoar, coarse loosely-bonded crystals	5 to 10	0.15 to 0.30

*The density ranges are only approximate. However, they indicate the differences one may expect between the various layers.

The virtually unbroken tundra snow surface has an albedo (surface reflectivity) of about 80%. When the snow disappears, in late May or early June, it goes rapidly and the albedo drops to about 15%. This five-fold decrease in albedo occurs at the same time when the amount of incident radiation is rapidly increasing, and results in a dramatic change in the amount of absorbed radiation at the surface (Weller, et al., 1972; Benson, et al., 1975). Similar observations were made on the Canadian tundra by McFadden and Ragotski (1967) who estimated a six-fold increase in absorbed radiation at the surface when the snow melted away. The best and most comprehensive treatment of the climatology of the Arctic Slope was written by Conover (1960).

Statement of the Problem

It is necessary to determine several parameters::

(1) the total precipitation which comes as Snow, P,

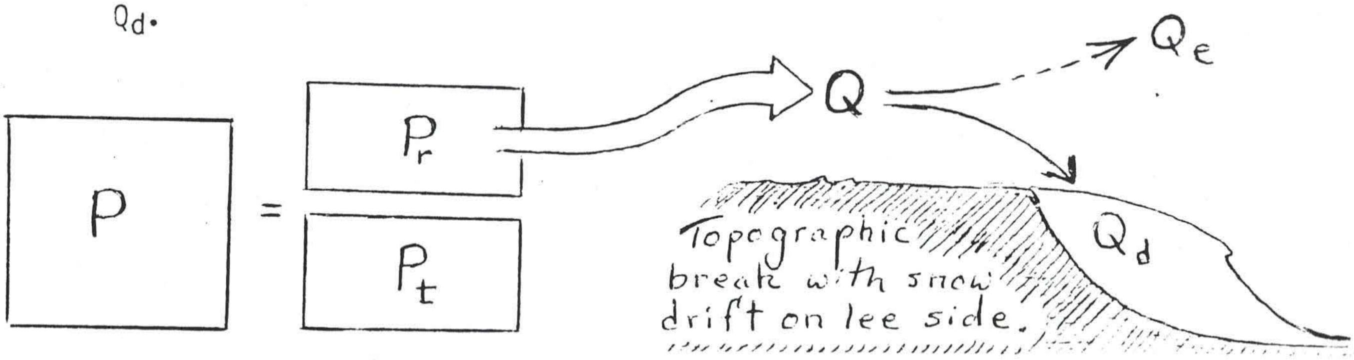
(2) the amount P_t which remains on the tundra after some snow has blown away and been concentrated in drifts.

(3) The amount P_r which is relocated by the wind,

(4) the amount of snow transport, Q, in water equivalent per unit width normal to the direction of wind transport.

(5) Part of the relocated snow is lost by sublimation in transport, this is Q_e.

(6) Part of the relocated snow is deposited in snow drifts, this is Q_d.



Our knowledge of the above parameters on the Arctic Slope is not good. The longest historical record of data relates the total precipitation but it requires critical evaluation. There are shorter records for the amount of snow on the tundra, and for the amount caught in drifts. Fortunately, only winds from two directions are effective in transporting snow; the prevailing winds from north-northeast move approximately twice as much snow as do the west winds which accompany occasional storms.

Precipitation Data - Unshielded Gauges

Weather observations on the Arctic coast of Alaska have been made by the U.S. Weather Bureau at Barrow since 1901, and at Barter Island since 1947. The precipitation data from Barrow are complete since 1924 (except for 1943), and since 1957 at Barter Island. These stations are separated by 520 km and they each use standard 8-inch precipitation gauges. Wind shields have been used on these gauges during some of the

time, but the records do not indicate when. During the 1970's they were not shielded. The annual recorded values, in millimeters of water equivalent, are summarized in table 1, with cumulative values plotted in Figure 1. These are the "raw data"; it is necessary to consider reasons for the changes in rates of precipitation, possible sources of error, and the approximate magnitudes of these errors, as well as the relative amounts of snow and rain.

The relative amounts of snow and rain represented by the raw data can be estimated by subdividing the year into nine "winter months", September through May, when all precipitation is assumed to fall as snow and three "summer" months, June through August when we assume that it falls as rain (Table 2). Although some snow fall has occurred in every month of the year this subdivision gives reasonable values and, if anything it errs on the side of slightly underestimating the amount of snowfall. Since the measurement errors systematically yield values less than the true precipitation, especially when it comes as snow, we can assume that the average value of about 60% snow is conservative (Table 2).

Table 2 shows slightly more total precipitation and snow fall at Barter Island than at Barrow. It also indicates considerable variability in precipitation from year to year, and a lack of synchronous behavior between Barrow and Barter Island.

The next step is to consider complications and possible errors in the data.

Complications Due to Wind Exposure

The records from standard 8-inch gauges are strongly dependent on the exact location of the station and its exposure. A station after having

TABLE 1

Annual precipitation and cumulative values at Barrow and Barter Island

	BARROW		BARTER ISLAND	
Year	Annual Precipitation mm H_2O	Cumulative Precipitation mm H_2O	Annual Precipitation mm H_2O	Cumulative Precipitation mm H_2O
1922	179			
1923	NO DATA	0		
1924	144	144		
1925	227	371		
1926	67	438		
1927	58	496		
1928	67	563		
1929	109	672		
1930	115	787		
1931	91	878		
1932	78	956		
1933	91	1047		
1934	41	1088		
1935	41	1129		
1936	49	1178		
1937	83	1261		
1938	155	1416		
1939	77	1493		
1940	75	1568		
1941	100	1668		
1942	164	1832		
1943	WET YEAR, NO DATA	*1832*		
1944	153	1985		
1945	78	2063		
1946	111	2174		
1947	52	2226		
1948	114	2340	NO DATA	
1949	104	2444	94	
1950	158	2602	233	
1951	136	2738	160	
1952	102	2840	225	
1953	70	2910	185	
1954	140	3050	NO DATA	
1955	115	3165	ESTIMATED	
1956	110	3275	NO DATA	0
1957	185	3460	230	230
1958	184	3644	94	324
1959	171	3815	137	461
1960	115	3930	103	564
1961	126	4056	249	813
1962	180	4236	195	1008
1963	248	4484	227	1235
1964	78	4562	130	1365
1965	149	4711	165	1530

TABLE 1 (Continued)

	BARROW		BARTER ISLAND	
Year	Annual Precipitation mm H_2O	Cumulative Precipitation mm H_2O	Annual Precipitation mm H_2O	Cumulative Precipitation mm H_2O
1966	139	4850	230	1760
1967	119	4969	244	2004
1968	84	5053	145	2149
1969	84	5137	96	2245
1970	47	5184	107	2352
1971	78	5262	189	2541
1972	125	5387	119	2660
1973	182	5569	107	2767
1974	78	5647	74	2841
1975	123	5770	84	2925
1976	73	5843	128	3053
1977	83	5926	85	3138
1978	98	6024	91	3229
1979	76	6100	167	3396
1980				

Summary Calculation of Average Rates of Precipitation for Selected Time Intervals (see Figure 1)

Years	mm		Δ ppt	Years	mm/yr
Barrow					
1925-1942	(371-1832)	=	1461	17	86
1927-1942	(496-1832)	=	1336	15	89
1944-1955	(1985-3165)	=	1180	11	107
1955-1966	(3165-4850)	=	1685	11	153
1966-1979	(4850-6100)	=	1250	13	96
Barter Island					
1957-1967	(230-2004)	=	1774	10	177
1967-1979	(2004-3396)	=	1392	12	116

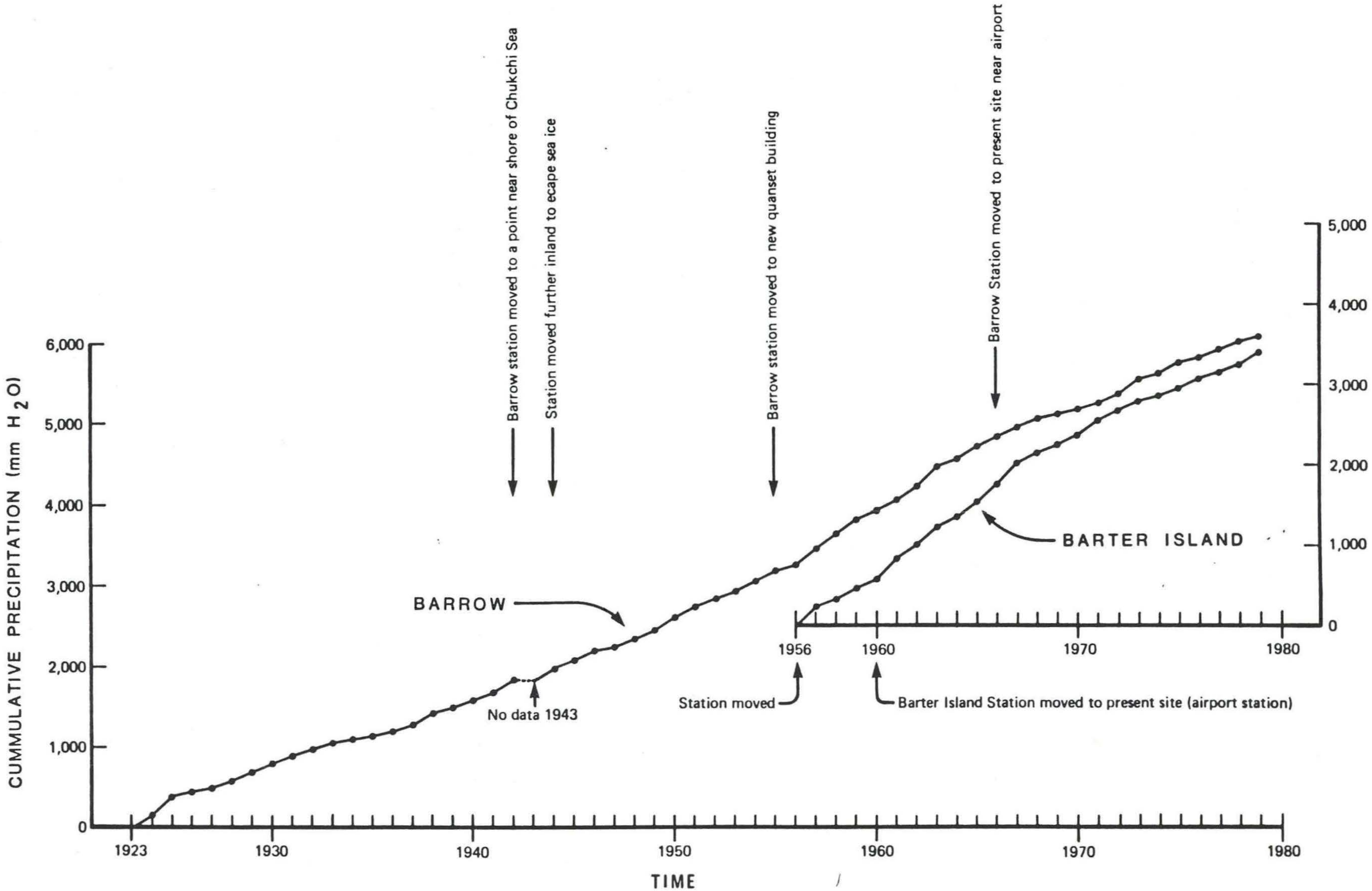


Figure 1

Cumulative precipitation at Barrow and Barter Island

TABLE 2

Seasonal precipitation at Barrow and Barter Island

Year	Season		Barrow mm	Barrow %	Barter Island mm	Barter Island %
1961-1962	1 Sept-31 May	snow	94	56	168	71
	1 June-31 Aug	rain	73	44	69	29
		Total	166	100	237	100
1962-1963	1 Sept-31 May	snow	141	55	142	64
	1 June-31 Aug	rain	115	45	79	36
		Total	256	100	221	100
1963-1964	1 Sept-31 May	snow	55	73	76	54
	1 June-31 Aug	rain	20	27	65	46
		Total	75	100	141	100
1964-1965	1 Sept-31 May	snow	69	61	71	48
	1 June-31 Aug	rain	44	39	79	52
		Total	113	100	150	100
1965-1966	1 Sept-31 May	snow	91	55	76	39
	1 June-31 Aug	rain	75	45	116	61
		Total	166	100	192	100
1966-1967	1 Sept-31 May	snow	68	57	190	66
	1 June-31 May	rain	52	43	99	34
		Total	120	100	289	100
1967-1968	1 Sept-31 May	snow	66	78	97	61
	1 June-31 May	rain	18	22	62	39
		Total	84	100	159	100
1968-1969	1 Sept-31 May	snow	68	64	45	42
	1 June-31 May	rain	38	36	62	58
		Total	106	100	107	100
1969-1970	1 Sept-31 May	snow	32	71	61	72
	1 June-31 May	rain	13	29	24	28
		Total	45	100	85	100
1970-1971	1 Sept-31 May	snow	41	53	69	43
	1 June-31 Aug	rain	37	47	92	57
		Total	78	100	161	100
1971-1972	1 Sept-31 May	snow	30	48	109	70
	1 June-31 Aug	rain	32	52	47	30
		Total	62	100	156	100
1972-1973	1 Sept-31 May	snow	110	52	68	60
	1 June-31 Aug	rain	103	48	45	40
		Total	213	100	113	100
1973-1974	1 Sept-31 May	snow	68	62	40	43
	1 June-31 Aug	rain	42	38	54	57
		Total	110	100	94	100
1974-1975	1 Sept-31 May	snow	44	37	28	50
	1 June-31 Aug	rain	74	63	28	50
		Total	118	100	56	100
1975-1976	1 Sept-31 May	snow	33	61	112	80
	1 June-31 Aug	rain	21	39	28	20
		Total	54	100	140	100
1976-1977	1 Sept-31 May	snow	62	70	50	65
	1 June-31 Aug	rain	27	30	27	35
		Total	89	100	77	100
1977-1978	1 Sept-31 May	snow	50	55	52	59
	1 June-31 Aug	rain	41	45	36	41
		Total	91	100	88	100
1978-1979	1 Sept-31 May	snow	52	55	60	48
	1 June-31 Aug	rain	43	45	66	52
		Total	95	100	126	100

Year	Season		Barrow $\bar{x}$	Barrow s	Barrow %	Barter Island $\bar{x}$	Barter Island s	Barter Island %
1961-1979	Overall mean	snow	65	29	58	84	45	59
		rain	48	29	42	60	26	41
		Total	113		100	144		100

operated for many years, may be found to lie in a local precipitation shadow which is quite unrepresentative of the area around it. This problem is most serious where there are only a few isolated stations in a large area. In addition to problems caused by the location of stations, precipitation gauges systematically err on the side of underestimating the amount of precipitation. This has been demonstrated repeatedly, including studies in Greenland where more than 20 years of snow strata on the ice sheet were compared with data from coastal weather stations (Benson, 1962). The percent of precipitation caught by standard, unshielded precipitation gauges decreases with increasing wind speed (Brooks, 1938; Wilson, 1954), regardless of whether the precipitation is in the form of rain or snow, but catches as low as 25% of the total precipitation occur during snowstorms. Considerable experimental work has been done on improving the collection efficiency of precipitation gauges (Warnick, 1953), and, to date the best system for wind-swept areas appears to be the Wyoming Blow Fence developed by Rechard and Larson (1971).

The gauges at Barrow had been shielded some of the time but the records do not indicate when. Possibly, the higher rate of precipitation at Barrow between 1955 and 1966 indicates that the gauge was shielded during this time but not before or after. The station was moved at the beginning and end of this period. Table 1 shows that the rate of precipitation within this period was 1.4 times greater than the previous period and 1.6 times greater than the following period. In other words, precipitation rates during the decades preceding and following the decade at the New Quonset Building, were both lower by a factor of about 1.5. One cannot help suspecting that moving the station may have had some control over this.

The record for Barter Island also shows a 1.5 times higher rate of precipitation during this period, and its station location was also moved at the beginning of the period. Unfortunately, the data preceding 1957 are incomplete. As with Barrow there is no indication as to when the Alter wind shield was on the gauge. However, as mentioned above, it is known that both gauges were not shielded during the 1970's.

In general, the evaluation of precipitation gauge records becomes more complex for snowfall than for rainfall because of the greater sensitivity of snow to wind action. On the Arctic Slope snow is always more than 50% of the total annual precipitation and may be as high as 80%. The net result is that precipitation in this region is greater than recorded. Black (1954) was the first to quantify this problem; by comparing precipitation data with the water equivalent of snow on the tundra, he showed that the Weather Bureau gauge at Barrow was recording only 25% to 50% of the actual precipitation.

A study of Arctic Slope snow cover, by working directly with the deposited snow strata, has been underway since 1961. It has been based on techniques developed in the Swiss Alps, the Sierra Nevada Mountains and on the Greenland and Antarctic ice sheets (Bader et al., 1939; Benson, 1962, 1967, 1969; Benson et al., 1975).

Natural drift traps on the Meade River selected in 1962, turned out to be the best of many such sites, and the amount of snow deposited in them has been measured during thirteen out of the seventeen years 1962 to 1979 as discussed below. In addition to this, at the suggestion of Martinelli, Tabler and Schmidt,* we installed several precipitation

*Of the U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station.

gauges shielded by the Wyoming Blow-Fence. Precipitation amounts in these gauges were to be compared with snow on the ground, and with precipitation recorded in the standard Weather Bureau gauges. Our objective was to use these Wyoming-shielded gauges as a standard to compare with Weather Service records and with the snow remaining on the tundra after wind action.

The first gauge, shielded by a Wyoming Blow Fence, was installed near the Naval Arctic Research Laboratory at Barrow in November 1975 and the second one at Atkasook, Meade River (100 km southwest of Barrow) in December 1975. These sites were selected for several reasons:

(1) The gauge data at Barrow could be directly compared with the Weather Bureau record at Barrow,

(2) the gauge at Meade River was placed adjacent to the site of long-term measurements on large snowdrifts.

(3) the logistics were simplified by using the Naval Arctic Research Laboratory as a base.

Gauges were then built at Kaktovik (Barter Island), Prudhoe Bay, Kavik and on the Jago River. Permits to install them were obtained from the State of Alaska Division of Lands and from the U.S. Fish and Wildlife Service, Dept. of Interior. The latter permit was required because the Jago River site is within the Arctic Wildlife Range. The Jago River site was selected so we could investigate an apparent zone of low precipitation between Barter Island and the Brooks Range.

Modifications were made in the details of installation of these gauges to make them more easily portable by light aircraft. The basic geometry of the Wyoming Blow-Fence was not altered, but the weight of the entire installation was reduced. We took maximum advantage of the

low temperature environment by drilling holes for support members into the perennially frozen ground.

Results from the first year of operating these gauges, were consistent in showing 3 to 5 times more precipitation than the gauges operated by National Weather Service. These results were summarized in Northeast by East, Vol. 1, No. 3, Sept. 1976.

The successful installation and operation of the Wyoming Blow-Fence at six sites on the Arctic Slope stimulated other agencies to install them as well. Two were built by the Soil Conservation Service on Seward Peninsula, three on the Arctic Slope by CRREL, two in Interior Alaska, at the Caribou-Poker Creeks Research Watershed, by the Forest Service, and one at Delta Junction by the University of Alaska.

In addition to the total of 14 gauges in Alaska, two more were built by the Arctic Gas study company on the Arctic Slope of the Yukon Territory.

The data from all of these gauges are now routinely reported in:

"Snow Surveys and Water Supply Outlook for Alaska", published in Feb., March, April, May and June of each year by the U.S. Dept. of Agriculture, Soil Conservation Service, Anchorage, Alaska.

The installation and maintenance of snow survey courses in the Western states, and in Alaska, is the primary responsibility of the Soil Conservation Service (SCS) of the U.S. Department of Agriculture. In the spring of 1975 the SCS snow survey reports included one hundred and twenty-nine (129) snow courses. This represented a marked and rapid increase from the ten (10) courses which existed in 1961. However, all of these courses were located in eastern Alaska and only one of them is north of the Brooks Range. In general, snow courses are not located above timberline because of the complications caused by drifting; this, of course, rules out the entire Arctic Slope of Alaska.

The establishment of precipitation gauges shielded by the Wyoming Blow-Fence, which began with this study, has augmented the basic SCS network in Alaska and provided coverage on the Arctic Slope. All of these gauges have now been turned over to the SCS and the total number of snow courses and Wyoming gages was 150 in the Spring of 1980.

It is significant that the number of these specially shielded gauges in Alaska and the Yukon increased from none in September 1975 to 15 in a period of sixteen months. The location of the gauges is as follows:

Wyoming Shield Locations

Place Name	Latitude	Longitude	Altitude (m)
Barrow	71°20'N	154°40'W	6
Meade River	70°29'N	157°25'W	10
Barter Island	70° 7'N	143°38'W	10
Prudhoe Bay	70°16'N	148°34'W	10
Kavik River	69°41'N	146°53'W	200
Jago River	69°42'N	143°36'W	170
Seward Peninsula	66° 0'N	162°00'W	
	65°40'N	162°25'W	
Caribou Peak (Poker Flat)	65° 0'N	147°30'W	760
Helmer's Ridge (Poker Flat) Part of Caribou-Poker Creeks Research Watershed	65° 0'N	147°30'W	630
Point Hope	68°21'N	166°43'W	6
Sagwon	69°23'N	148°40'W	370
Toolik	68°39'N	149°20'W	1000
Delta Junction	64°00'N	145°44'W	~~389~~ 390

Complications Due to "Traces"

Another source of error in weather station records comes from the slow rates of snowfall in Arctic areas combined with the six-hourly schedule of observations. This frequently results in a run of "traces"

being recorded, which are not entered quantiatively in the records (Jackson, 1960). At both Barrow and Barter Island there are a large number of "traces" in the precipitation records. During the calendar year 1978 at Barrow there were 282 days with recorded precipitation, but 192 of these days (68%) showed only "T" (for trace). These 192 entries of T add up to zero in the annual precipitation record, and the error introduced by this is unknown. At Barter Island during the 1970's: 1973 showed 197 days with T, out of 259 precipitation days (76%); 1974 showed 180 T out of 240 (75%), and 1975 showed 178 T out of 269 (66%).

In order to examine the extent of traces in the record at Barrow and Barter Island the precipitation data have been broken down into monthly values for the seven year period 1972 to 1979 (Tables 3 and 4). In both cases Trace recordings make up more than 60% of the total number of days during which precipitation was recorded, with about 5% more Traces in winter than in summer.

The values at these two arctic stations may be put in perspective by comparing them with other places which have greater quantities and rates of precipitation. The number of days on which trace was recorded compared with the total number of days with precipitation, at fourteen Alaska weather stations, are summarized in Table 5. Clearly, the percentage of trace in the record is inversely proportional to the amount of precipitation.

The data from Table 5, plotted in Figure 2, show a surprisingly consistent relationship which can be well described by:

$$T = \frac{A}{\sqrt{P}} ,$$

TABLE 3

Traces in the monthly precipitation records at Barrow for the years 1972 to 1979, with seven year averages for snow and rain.

BARROW

1972-1973	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	34	7	27			
Oct	36	13	28			
Nov	11	9	16			
Dec	4	7	14		Snow	
Jan	2	15	19			
Feb	4	9	13	110	95	172
Mar	1	9	12	55% Trace		
Apr	13	10	18			
May	5	16	25			
Jun	20	18	25		Rain	
Jul	27	4	22	103	32	74
Aug	56	10	27	43% Trace		

1973-1974	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	29	11	27			
Oct	14	9	27			
Nov	9	15	26			
Dec	2	11	15		Snow	
Jan	10	8	19			
Feb	2	10	13	68	107	176
Mar	T	11	12	61% Trace		
Apr	T	12	12			
May	2	20	25			
Jun	13	17	27		Rain	
Jul	14	12	21	42	39	66
Aug	15	10	18	59% Trace		

1974-1975	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	12	13	23			
Oct	5	10	18			
Nov	4	13	20			
Dec	1	15	16		Snow	
Jan	4	9	17			
Feb	7	13	22	44	113	179
Mar	4	11	22	63% Trace		
Apr	5	10	14			
May	2	21	27			
Jun	20	18	27		Rain	
Jul	25	9	24	74	39	78
Aug	29	12	27	50% Trace		

1975-1976	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	13	18	29			
Oct	10	16	27			
Nov	2	15	21			
Dec	T	16	17		Snow	
Jan	1	17	20			
Feb	2	14	17	33	149	196
Mar	1	17	19	76% Trace		
Apr	3	15	22			
May	1	21	24			
Jun	8	14	21		Rain	
Jul	9	14	21	21	44	64
Aug	4	16	22	69% Trace		

TABLE 3 (Continued)

BARROW (Continued)

1976-1977	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	18	10	31			
Oct	15	10	31			
Nov	11	14	26			
Dec	1	18	19	Snow		
Jan	4	12	21			
Feb	4	14	19	62	121	211
Mar	5	7	16	57% Trace		
Apr	1	16	20			
May	3	20	28			
Jun	5	21	25	Rain		
Jul	2	7	10	27	40	58
Aug	20	12	23	69% Trace		

1977-1978	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	20	18	29			
Oct	12	7	27			
Nov	1	14	18			
Dec	5	15	23	Snow		
Jan	2	13	19	50	138	205
Feb	4	12	19	67% Trace		
Mar	2	19	24			
Apr	3	17	20			
May	1	23	26			
Jun	9	21	27	Rain		
Jul	19	11	26	41	52	80
Aug	13	20	27	65% Trace		

1978-1979	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	28	12	28			
Oct	3	21	28			
Nov	8	9	20			
Dec	6	14	18	Snow		
Jan	1	9	12			
Feb	T	7	7	52	106	157
Mar	2	8	10	68% Trace		
Apr	3	4	9			
May	1	22	25			
Jun	3	13	18	Rain		
Jul	21	9	18	43	31	61
Aug	19	9	25	51% Trace		

% Trace in the precipitation record for the seven years 1972-1979

	Average	Standard Deviation
Winter Snow	63%	5
Summer Rain	58%	10

TABLE 4

Traces in the monthly precipitation records at Barter Island for the years 1972 to 1979, with seven year averages for snow and rain.

BARTER ISLAND

1972-1973	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	11	10	23			
Oct	18	20	27			
Nov	4	12	18			
Dec	5	20	27	Snow		
Jan	9	20	24			
Feb	1	22	23	68	157	207
Mar	T	18	18	76% Trace		
Apr	5	18	25			
May	15	17	22			
Jun	13	16	20	Rain		
Jul	10	7	15	45	34	55
Aug	22	11	20	62% Trace		

1973-1974	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	17	17	23			
Oct	12	15	28			
Nov	3	17	21			
Dec	T	19	20	Snow		
Jan	2	13	18			
Feb	1	18	20	40	146	183
Mar	T	22	22	80% Trace		
Apr	1	10	11			
May	4	15	20			
Jun	21	12	19	Rain		
Jul	14	8	16	54	28	53
Aug	19	8	18	53% Trace		

1974-1975	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	5	12	20			
Oct	3	22	29			
Nov	2	17	21			
Dec	2	23	26	Snow		
Jan	4	15	23			
Feb	5	11	21	28	164	212
Mar	1	19	21	77% Trace		
Apr	5	21	26			
May	1	24	25			
Jun	8	22	29	Rain		
Jul	12	10	17	28	35	62
Aug	8	3	16	56% Trace		

1975-1976	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	14	7	16			
Oct	14	13	31			
Nov	8	11	19			
Dec	6	22	25	Snow		
Jan	5	19	24			
Feb	8	11	17	112	111	194
Mar	22	9	21	57% Trace		
Apr	5	8	18			
May	30	11	23			
Jun	12	8	14	Rain		
Jul	10	8	14	28	29	45
Aug	6	13	17	64% Trace		

TABLE 4 (Continued)

BARTER ISLAND (Continued)

1976-1977	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	5	10	24			
Oct	13	10	24			
Nov	8	16	24			
Dec	3	10	14	Snow		
Jan	5	13	20			
Feb	4	12	17	50	101	171
Mar	1	10	15	59% Trace		
Apr	7	5	12			
May	4	15	21			
Jun	14	12	18	Rain		
Jul	T	9	9	27	30	44
Aug	13	9	17	68% Trace		

1977-1978	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	4	12	19			
Oct	25	11	25			
Nov	3	10	18			
Dec	4	12	18	Snow		
Jan	5	14	20			
Feb	4	12	19	52	99	160
Mar	2	11	15	62% Trace		
Apr	3	7	10			
May	2	10	16			
Jun	15	12	21	Rain		
Jul	5	10	17	36	33	62
Aug	16	11	24	53% Trace		

1978-1979	mm H_2O	T_d	P_d	mm H_2O	T_d	P_d
Sept	13	8	22			
Oct	18	7	24			
Nov	6	6	15			
Dec	4	7	14	Snow		
Jan	4	10	17			
Feb	1	8	10	60	75	145
Mar	3	9	13	52% Trace		
Apr	6	7	12			
May	5	13	18			
Jun	17	9	16	Rain		
Jul	20	11	20	66	34	63
Aug	29	14	27	54% Trace		

% Trace in the precipitation record for the seven years 1972-1979

	Average	Standard Deviation
Winter Snow	64.5%	11.4
Summer Rain	59.0%	6.4

TABLE 5

Percentage number of days with "Trace" in the total number of days with Precipitation at fourteen Alaskan weather stations

Station	(mm)	T_d	P_d	% Trace Average	% Trace Standard Deviation
Barrow	124	1119	1781	63	5
Barter Island	179	1061	1645	64	9
Gulkana	282	459	1009	46	4
Fairbanks	285	570	1304	43	9
Anchorage	374	583	1397	42	6
Nome	418	584	1442	41	7
McGrath	425	494	1445	34	3
St. Paul Island	623	772	2136	34	8
Talkeetna	727	373	1333	28	6
Juneau	1389	346	1902	18	2
Kodiak	1440	357	1793	20	4
Valdez	1506	189	1069	18	3
Annette	2903	292	1859	16	3
Yakutat	3364	236	1913	12	3

The percentage data all refer to the seven years 1972-1979, except Valdez which refers to the five years 1974-1979.

The Long-Term Normal values extend back to 1941 at most stations.

T_d = Days with Trace in the seven years 1972-1979.

P_d = All days with Precipitation in the seven years 1972-1979.

where $T = \frac{T_d}{P_d}$ expressed in %

T_d = Number of days showing Trace in the precipitation record

P_d = Number of days showing precipitation of any amount, including Trace

P = The normal annual precipitation (in mm H_2O) measured over the years 1941 to 1979, in most cases.

A = A constant, with units of (mm $H_2O)^{1/2}$

The value of A is 750 ± 50; the curves drawn in Figure 2 are for A = 700 and 800. These values become simply 7 and 8 if one does not wish to express the ratio T_d/P_d in percent.

A Trace in the record is interpreted as less than 0.13 mm H_2O in a measurement period. Thus, at Barrow or Barter Island during a calendar year, with 190 entries of T, this could amount to 25 mm H_2O, which is about 20% of the recorded annual values. Brown et al. (1968) attempted to apply a correction for traces in the summer rain records by assigning a value of 0.06 mm H_2O to them. They concluded that an adequate overall correction could be obtained for the summer record by simply multiplying it by 1.1; but a higher, and unknown, correction factor was needed for the winter data. Dingman et al. (1980) used a conservative factor of 1.6 for the winter record based on the data in Table 6. However, they knew this value was too low because it is based on the amount of snow, P_t, remaining on the open tundra after some has blown away and been concentrated in drifts. One of the goals of the present study is to determine a realistic correction factor for the winter precipitation records. In referring to this work, in its preliminary stages, Dingman et al. (1980, p. 53) pointed out that "the correction factor may be about 3 rather than our conservative estimate of 1.6".

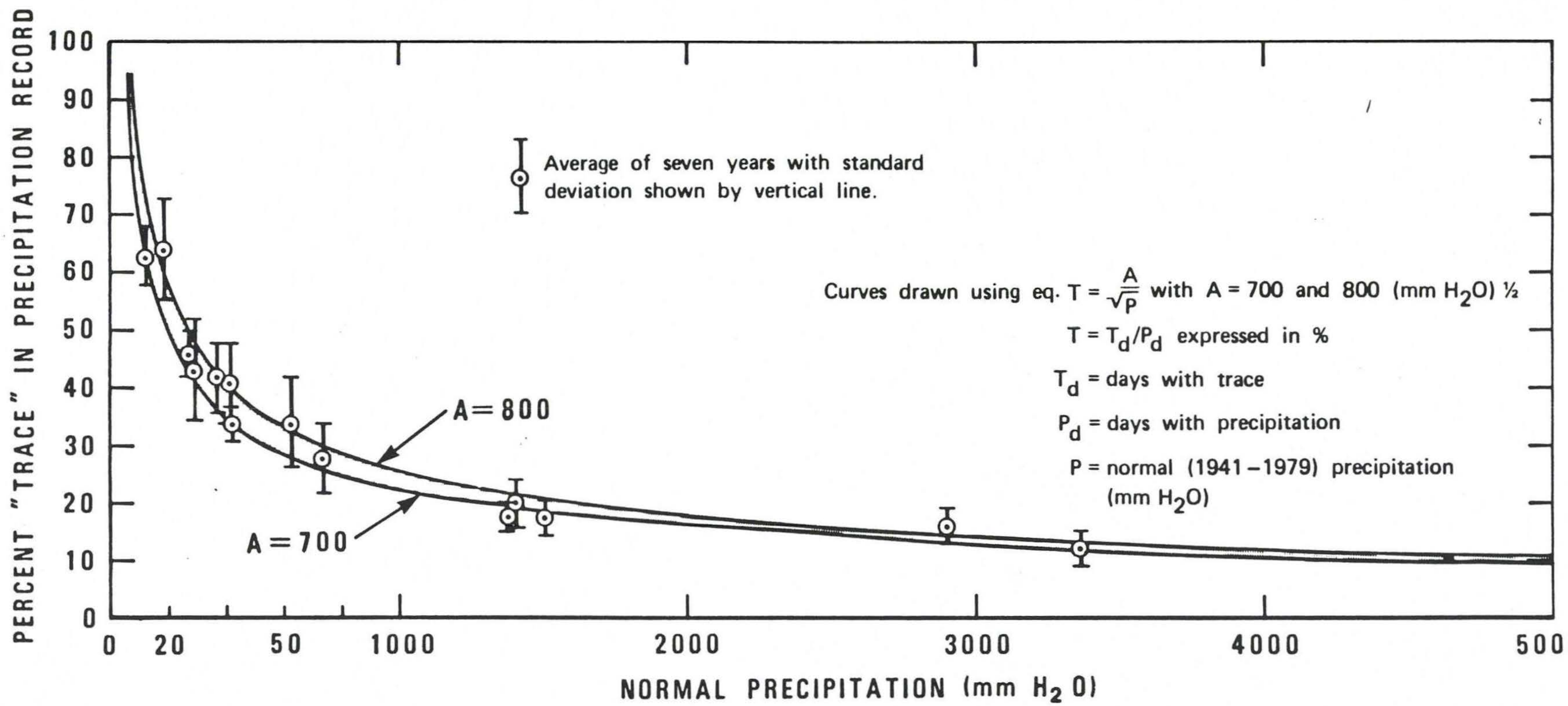


Figure 2

Percent of "Trace" in the precipitation record plotted as a function the amount of precipitatation for 14 Alaskan weather stations (see Table 5)

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Comparison of Precipitation Records from Unshielded Gauges with Snow on the Tundra

The first direct comparison of snow on the tundra at Barrow with precipitation records, also at Barrow, was made during the 1949-50 winter by Black (1954). His measurement of between 102 and 232 mm of water equivalent in the tundra snow was compared with the Weather Bureau record of 56 mm from 1 September 1949 to 31 May 1950. Thus, the precipitation gauge caught 24 to 55% of the amount on the tundra.

Between 1962 and 1974 six sets of measurements were made on probe-traverses within a large area (approximately 25 km^2) southwest of the Naval Arctic Research Laboratory at Barrow. The location of the test area and a description of it are given by Brown et al. (1980). It proved difficult to obtain a single number for the water equivalent because snow depth varied from nothing on hummocks to more than 3 meters in drifts. Thus, ranges of values were recorded for individual traverses. Snow drifts at several sites in the Barrow area were measured separately. All available data from the tundra near Barrow, including those from Black (1954), are summarized in Table 6. The data from 1962 to 1974, obtained by Benson, are partly summarized by Dingman et al. (1980).

The data in Table 6 provide a minimum estimate of the extent by which the unshielded precipitation gauge underestimates the true precipitation. Thus, the average gauge record is at least 40% too low. This is a minimum estimate because the snow remaining on the tundra, P_t, is, in itself, less than the amount precipitated. Some of the total amount of snow is always relocated by wind, P_r, and either evaporated, Q_e, or deposited as snow drifts, Q_d, in topographic "drift traps" such as lake or river banks and other depressions. However, on the

TABLE 6

Water Equivalent of Snow on the Barrow Tundra Compared with Weather Station Precipitation Records

Year	Snow Depth (cm) Most Frequent Range	Snow Depth (cm) Best Value	Snow Density ($g\ cm^{-3}$) Most Frequent Range	Snow Density ($g\ cm^{-3}$) Best Value	Water Equivalent of Snow on Tundra (mm H_2O) Best Estimate	Water Equivalent of Snow on Tundra (mm H_2O) Extreme Range**	USWB Precip. Records 1 Sept-31 May (mm H_2O)	*** Precip. Record % of Snow on Tundra
1949-50	25 to 58	*	--*	0.40	*	102 to 232	56	24 to 55%
1962-63	30 to 40	35	0.36 to 0.46	0.42	144 ± 17	108 to 184	141	98%
1969-70	15 to 20	17	0.32 to 0.40	0.36	61 ± 07	48 to 80	32	53%
1970-71	25 to 45	35	0.32 to 0.40	0.36	126 ± 14	80 to 180	41	32%
1971-72	25 to 35	30	0.32 to 0.40	0.36	108 ± 12	80 to 140	30	28%
1972-73	30 to 40	33	0.32 to 0.40	0.36	119 ± 13	96 to 160	110	92%
1973-74	30 to 40	34	0.32 to 0.40	0.36	122 ± 14	96 to 160	68	56%
Average and standard deviation (1949-1950 omitted)					113 ± 28		70 ± 46	62%
1969-1970 omitted also					124 ± 13		78 ± 47	63%

*The 1949-50 data are from Black (1954, p. 205), he cited four maximum average values and a single density value of 0.40 g cm^{-3}. All other data measured by Benson.

**This extreme case was calculated by using the lowest values of both depth and density to obtain the lower end, and the highest combination of values to obtain the upper end. Thus, it defines a wider range of values than one should expect; nevertheless, the precipitation-gauge record falls below this extreme range in five out of the seven cases studied.

***These values compare the water equivalent of snow on the Tundra in "Best estimate" column with the record from the precipitation gauge.

average these data for P_t show that the gauge record misses <u>at least</u> 40% of the actual precipitation.

The data also show that the error of underestimation becomes less during years with increased precipitation. This is strikingly the case for 1962-63 and 1972-73 which are the years with most snowfall during the 19 years summarized in Table 2.

The erosion and deposition accompanying wind action tend to smooth irregularities on the snow surface. This causes the tundra snow cover to appear similar from one year to the next. It also results in a smaller standard deviation of the water equivalent of tundra snow when compared to that of the precipitation gauge record. If the year 1969-70 is omitted, because its snow cover is only half of the normal amount, the differences in standard deviations increase markedly. With the 1969-1970 data, the standard deviation from snow measurements is 61% of that from the precipitation gauge records; if 1969-70 data are omitted this comparative value drops to 28%. The 1969-70 year is interesting in that it showed below normal precipitation at both Barrow and Barter Island yet the maximum flux of windblown snow, between 1962 and 1979, was measured during this year at Atkasook on the Meade River. This point is discussed below (see Fig. 4 and Table 11).

Another indication of the extent of underestimation provided by the gauge records is obtained by comparing them with what is listed as the "extreme range" in Table 6. This extreme range was calculated by using the lowest values of both depth and density to define the lower end, and the highest combination of values to define the upper end. Thus, it defines a wider range of values than one should reasonably expect. However, the precipitation gauge record falls below this extreme range

in five out of the seven cases studied. The two cases where the precipitation gauge records lie within the extreme range are the two highest values for winter snow between 1961 and 1979 (see Table 2).

Comparison of Precipitation Records from Unshielded Gauges with Records from Gauges Shielded by the Wyoming Blow-Fence

The Wyoming Blow Fence as a wind shield around precipitation gauges has provided a powerful new tool in the measurement of precipitation in wind-swept regions. We believe that it provides as reasonable an estimate of precipitation of snow on Alaska's Arctic Slope as it does in the high plains of Wyoming (Rechard and Larson, 1971; Rechard, 1972). Data are now available from Wyoming Gauges at Barrow and Barter Island which can be compared directly with adjacent unshielded Weather Service precipitation gauges.

Data from the unshielded gauge compared with the Wyoming Gauge for four winters are summarized for Barrow in Table 7 and for Barter Island in Table 8. During the first two winters, 1975-76 and 1976-77, it was possible to obtain data several times during the winter. During the last two winters, 1977-78 and 1978-79, the gauge records could only be compared at the beginning and end of the winter. Unfortunately, due to confusion at Barter Island in spring 1978 the gauge was dumped without being weighed, so the year's record was lost. Nevertheless, the data clearly indicate that the Wyoming gauge consistently catches more precipitation at both Barrow and Barter Island by a factor of about 3.

The Wyoming gauges and the unshielded gauges respond in harmony to variations in the quantity of precipitation from year to year at Barrow and Barter Island. This is seen by comparing the ratios of precipitation

TABLE 7

Comparison of records from the Wyoming gauge at Barrow, Alaska with the unshield Weather Bureau gauge at Barrow, Alaska.

BARROW

1975-76 Winter

Time Interval	Days	Precipitation (mm) Unshielded U.S.W.B. Gauge	Precipitation (mm) Wyoming Shielded Gauge	Ratio Wyo. Shield / No Shield
10-XII-75 to 16-IV-76	128	5.4	30.0	5.6 (Total Time)
10-XII-75 to 22-I-76	43	0.8	8.4	10.5
22-I-76 to 25-II-76	34	2.3	7.6	3.3 } 4.7 (Ave) } 6.6
25-II-76 to 16-IV-76	51	2.3	14.0	6.1

1976-77 Winter

Time Interval	Days	Unshielded U.S.W.B. Gauge	Wyoming Shielded Gauge	Ratio
20-IX-76 to 6-V-77	228	43.9	96.3	2.2 (Total Time)
20-IX-76 to 20-X-76	30	9.4	14.2	1.5
20-X-76 to 23-XI-76	34	15.7	27.4	1.7
23-XI-76 to 23-XII-76	30	3.8	11.2	2.9 } Average 3.0
23-XII-76 to 22-I-77	30	3.6	24.4	6.8
22-I-77 to 3-IV-77	71	10.2	19.0	1.9
3-IV-77 to 6-V-77	33	1.3	0	$\rightarrow\infty$?

1977-78 Winter

Time Interval	Days	Unshielded U.S.W.B. Gauge	Wyoming Shielded Gauge	Ratio
30-IX-77 to 1-V-78	213	29	91	3.1 (Total Time)

1978-79 Winter

Time Interval	Days	Unshielded U.S.W.B. Gauge	Wyoming Shielded Gauge	Ratio
1-X-78 to 1-VI-79	243	25	81	3.2 (Total Time)

Overall Average = 3.5

TABLE 8

Comparison of records from the Wyoming gauge at Barter Island, Alaska with the unshielded Weather Bureau gauge at Barter Island, Alaska.

BARTER ISLAND

Time Interval	Days	Precipitation (mm) Unshielded U.S.W.B. Gauge	Precipitation (mm) Wyoming Shielded Gauge	Ratio Wyo. Shield / No Shield
1975-76 Winter				
21-I-76 to 23-IV-76	94	37.3	84.3	2.3 (Total Time)
21-I-76 to 10-III-76	50	26.9	32.2	1.2
10-III-76 to 23-IV-76	44	10.4	52.1	5.0
				Average=3.1
1976-77 Winter				
4-X-76 to 13-IV-77	190	40.6	121.4	3.0 (Total Time)
4-X-76 to 6-XI-76	32	11.7	31.0	2.6
6-XI-76 to 22-XI-76	16	1.3	5.1	4.0
22-XI-76 to 21-XII-76	29	7.4	41.9	5.7
21-XII-76 to 8-II-77	49	14.0	27.9	2.0
8-II-77 to 3-III-77	23	3.0	5.1	1.7
3-III-77 to 13-IV-77	41	3.3	12.7	3.8
				Average=3.3
1977-78 Winter				
1-X-77 to 28-IV-78	210	Contents of gauge dumped out by U.S.W.B. personnel		
1978-79 Winter				
25-VIII-78 to 1-VI-79	273	60.0	147.3	2.5

Overall Average = 2.6 (s=.4)

recorded in the respective gauges at Barter Island and Barrow (Table 9). Unfortunately, the Wyoming gauge ratios could be calculated for only three years, they are slightly larger than the ratios from the unshielded precipitation gauges.

There is no Weather Service gauge at the Meade River site but the Wyoming gauges at Barrow and Meade River are compared in the right hand side of Table 9. The ratios indicate slightly more precipitation at Meade River than at Barrow, which agrees with the conclusions by Britton (1957) and by Clebsch and Shanks (1968), Perhaps of greater importance, the difference between records from the Wyoming gauges at Barrow and Meade River is less than that between Barrow and Barter Island. This is what one should expect because the distance between Barrow and Atkasook is only 18% of that between Barrow and Barter Island, and our first attempts to compare winds at Barrow and Atkasook show that they are in the same weather pattern (see also Britton, 1975; Clebsch and Shanks, 1968). It strengthens confidence in the validity of the records from Wyoming gauges.

A summary of data from all Wyoming gauges on the Arctic Slope is presented in Table 10. In most cases the time span is less than the 272 days (273 during leap years) between 1 September and 31 May which we consider to be the snow season. The percentage of the winter which is sampled is indicated in each case. It is left as an exercise for the reader to extrapolate the rate to the full winter period if he feels this would be useful. The available data support the idea of a zone of reduced precipitation near the Jago River site along the line from Barter Island to McCall Glacier. They also support the view that precipitation at Prudhoe Bay lies between the values for Barrow and

once a prof
always a prof
R.A.

TABLE 9

Ratios of records from shielded and unshielded gauges at Barrow and Barter Island, and of shielded gauges only between Barrow and Atkasook.

	Ratios: Barter Island / Barrow		Ratios: Meade River / Barrow
Winter snow	USWB Gauges	Wyo Gauges	Wyo Gauges
1961-1962	168/94 = 1.8		
1962-1963	142/141 = 1.0		(No USWB gauge is maintained at the Meade River site so this column compares only the Wyoming gauges.)
1963-1964	76/55 = 1.4		
1964-1965	71/69 = 1.0		
1965-1966	76/91 = 0.8		
1966-1967	190/68 = 2.8		
1967-1968	97/66 = 1.5		
1968-1969	45/68 = 0.7		
1969-1970	61/32 = 1.9		
1970-1971	69/41 = 1.7		
1971-1972	109/30 = 3.6		
1972-1973	68/110 = 0.6		
1973-1974	40/68 = 0.6		
1974-1975	28/44 = 0.6		
1975-1976	112/33 = 3.4	84.3/21.6 = 3.9	42/30 = 1.4
1976-1977	50/62 = 0.8	121.4/96.3 = 1.3	110/96 = 1.15
1977-1978	52/50 = 1.0	GAUGE DUMPED	79/91 = 0.87*
1978-1979	60/52 = 1.2	147.3/81 = 1.8	84/81 = 1.0
1979-1980			
	Ave. = 1.5 s = 0.9		

Note 1. Values for precipitation are given in mm of water (or water equivalent).

Note 2. The 1975-1976 record spans 273 days (from 1 Sept. to 31 May) for the Weather Bureau gauge at Barter Island but only from 92 days (from 21 Jan. to 23 April) for the Wyo gauge.

*Gauge at Meade River was found covered by snow and rime ice on 8 April 1978. Therefore, this was not a complete sample.

TABLE 10

Summary of data from Wyoming snow gauges on Alaska's Arctic Slope.

Station	Year	Time Span	Days	% of Winter*	Winter Snow (mm) Water Equivalent from Wyoming Gauge
Barrow	1976	10-XII-75 to 16-IV-76	128	47%	30
	1977	20-IX-76 to 6-V-77	228	84%	96
	1978	30-IX-77 to 1-V-78	213	78%	91
	1979	1-X-78 to 1-VI-79	243	89%	81
Meade River	1976	10-XII-75 to 16-IV-76	128	47%	42
	1977	20-IX-76 to 2-IV-77	194	71%	109
	1978	30-IX-77 to 13-V-78	226	83%	79**
	1979	1-X-78 to 8-V-79	220	81%	84
Barter Island	1976	21-I-76 to 23-IV-76	92	34%	84
	1977	4-X-76 to 13-IV-77	168	46%	125
	1978	1-X-77 to 28-IV-78	210		
	1979	25-VIII-78 to 1-VI-79	279	102%	147
Jago River	1976	--	-		-
	1977	6-X-76 to 12-IV-77	188	69%	109
	1978	--	-		-
	1979	25-VIII-78 to 31-V-79	279	102%	104
Kavik	1976	--	-		-
	1977	6-X-76 to 15-IV-77	188	69%	130
	1978	--	-		-
	1979	24-VIII-78 to 31-V-79	280	103%	142
Prudhoe Bay	1976	--	-		-
	1977	18-IX-76 to 15-IV-77	209	77%	137
	1978	30-IX-77 to 3-III-78	154	57%	84
	1979	26-IX-78 to 1-VI-79	247	91%	112
Toolik River	1976	--	-		-
	1977	20-IX-76 to 28-II-77	161	59%	84***
	1978	11-IX-77 to 5-V-78	236	87%	91
	1979	7-X-78 to 29-IV-79	204	75%	71
Sagwon	1976	--	-		-
	1977	--	-		-
	1978	4-IX-77 to 5-V-78	243	89%	94
	1979	7-X-78 to 29-IV-79	204	75%	188

*"Winter" means 272 days (1 September to 31 May).

**Gauge found covered by rime ice and snow on 8 April 1978.
***No measurement at end of winter.

Barter Island. The data all support the general conclusion that the arctic slope receives more precipitation than is recorded by the Weather Service gauges.

If we accept the correction factor of 1.1 for summer data referred to on page ~~15~~ 24, and apply the correction factor of 3, determined here, for winter data, we can revise the overall averages from the raw data of Table 2 as follows:

	Barrow	Barter Island
Snow (mm)	195 (80%)	252 (80%)
Rain (mm)	53 (20%)	66 (20%)
Total (mm)	248 (100%)	318 (100%)

The long term record at Fairbanks shows 280 mm of total precipitation; thus, it lies midway between the values for Barrow and Barter Island. Barrow receives 88% of the Fairbanks amount and Fairbanks receives 88% of the Barter Island amount.

Snow Relocated by Wind and Caught in Drift Traps

One of the outstanding features about the wind blown snow on the Arctic Slope is the similar pattern of drifts from one year to the next. This permitted us to select several sites for repeated annual measurements of large snow drifts. The late Robert Fischer (chief pilot for the Arctic Research Laboratory at Barrow) helped the writer select sites in 1961 and 1962, some of which have been studied ever since. The longest history of such measurements is from a pair of sites at Atkasook (70°29'N; 157°25'W) on the Meade River (Fig. 3), in the oriented lakes district about 95 km SSW of Barrow. The river banks are 10 to 20 m high in this area and the meander loops provide all possible directional exposures to wind drifting.

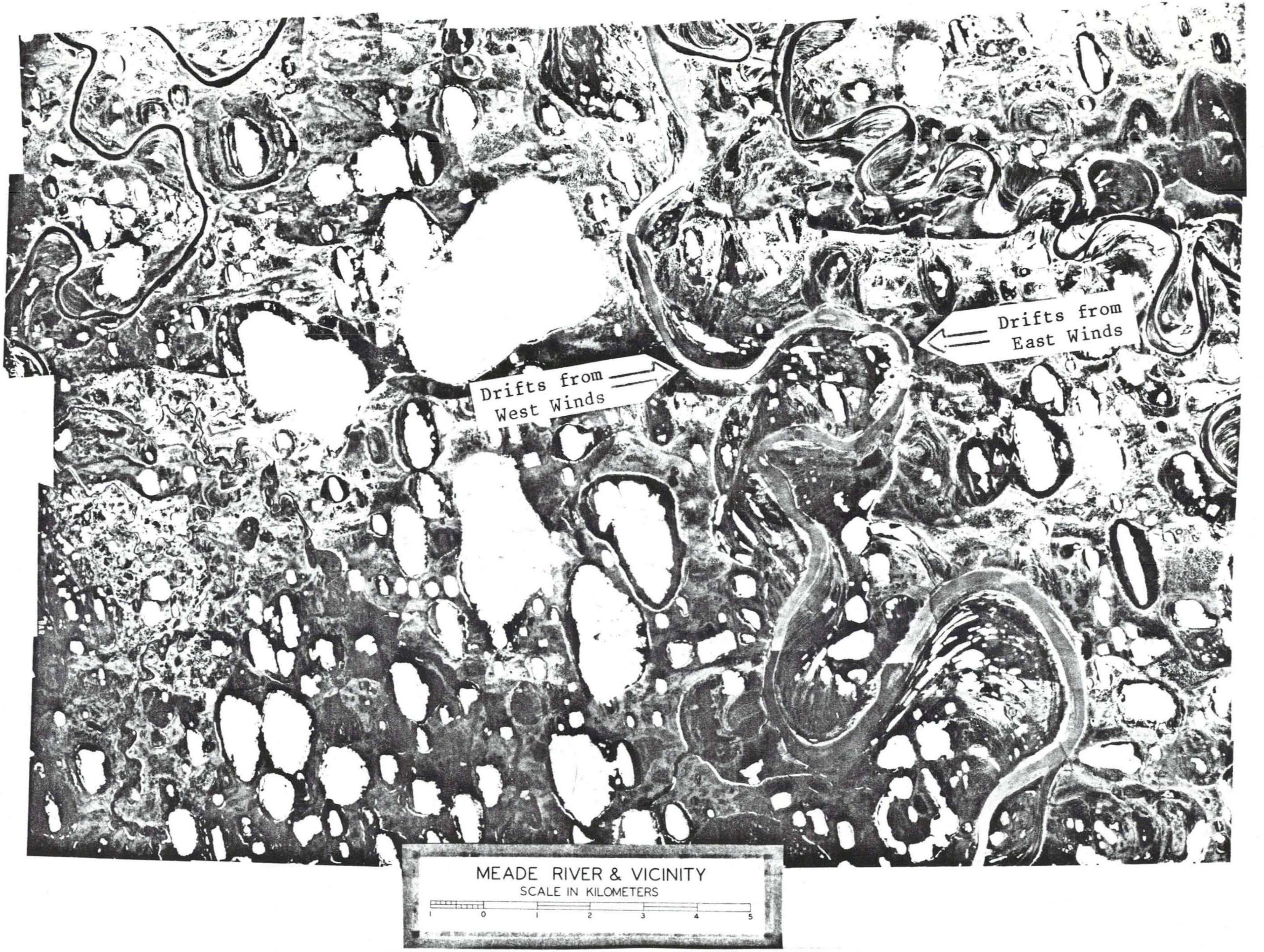

Figure 3

Aerial photograph of the Meade River region near Atkasook

There are two major wind directions which transport snow in this part of the Arctic Slope and they are nearly opposed to each other; one is from the west and the other is from north-northeast. The former is often associated with fresh precipitation while the latter is the prevailing wind. River banks oriented parallel to these wind directions do not form snow drifts, but banks perpendicular to them form large drifts of similar shape each year (Benson, 1969; Dingman et al., 1980).

Figure 4 shows cross-sections of the drifts formed from east and west winds at Atkasook over the 17 year period 1962 to 1979. The location of these cross sections is indicated on Figure 3. The bank which forms drifts from the east winds is nearly twice as high as the one which forms west wind drifts (20 and 10 m respectively). In each case the drift cross section extends 50 m from the top of the bank.

The cross sections were measured by a combination of methods. The topography of the upper surface was measured by leveling and the depth of snow was measured by probing. The bottom profiles of the drifts were measured by leveling in 1964 and 1975. The two surveys produced essentially identical profiles, so the banks were stable in form over the two decades spanned by these measurements even though they eroded back by several meters in places. The surveying information was essential because it proved impossible to probe through the drifts in some cases where depth exceeded 4 m, in especially hard wind packed snow or where thick ice layers were encountered.

The cross-section areas of the drifts in Figure 4 were graphically integrated and the water equivalent was determined for each 5 m horizontal increment (Table 11). Calculation of the water equivalent was complicated by the necessity to assign an average density to each 5 m horizontal increment individually, because the snow density increases with depth.

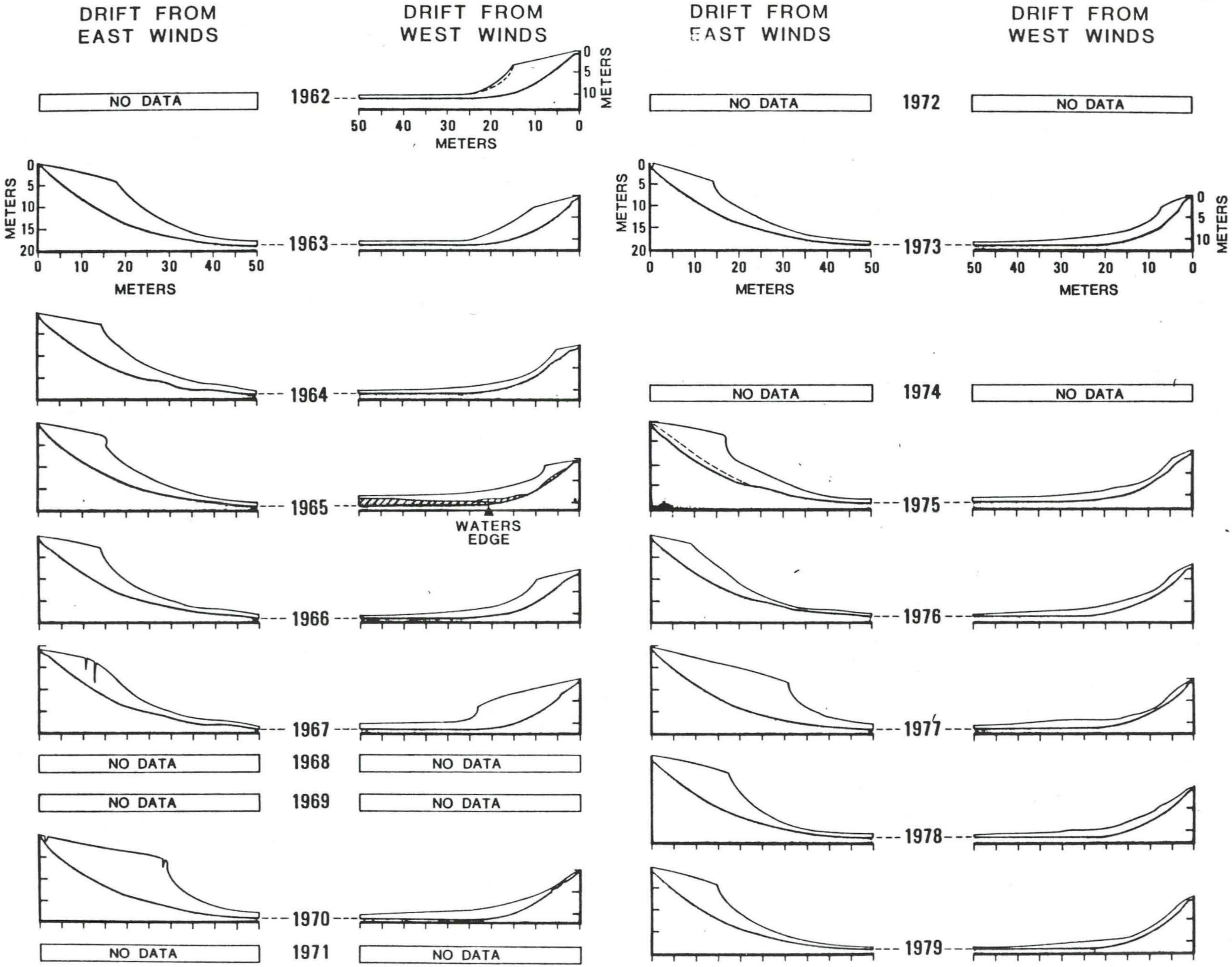

Figure 4

Snow drifts from east and west winds at Atkasook on the Meade River between 1962 and 1979

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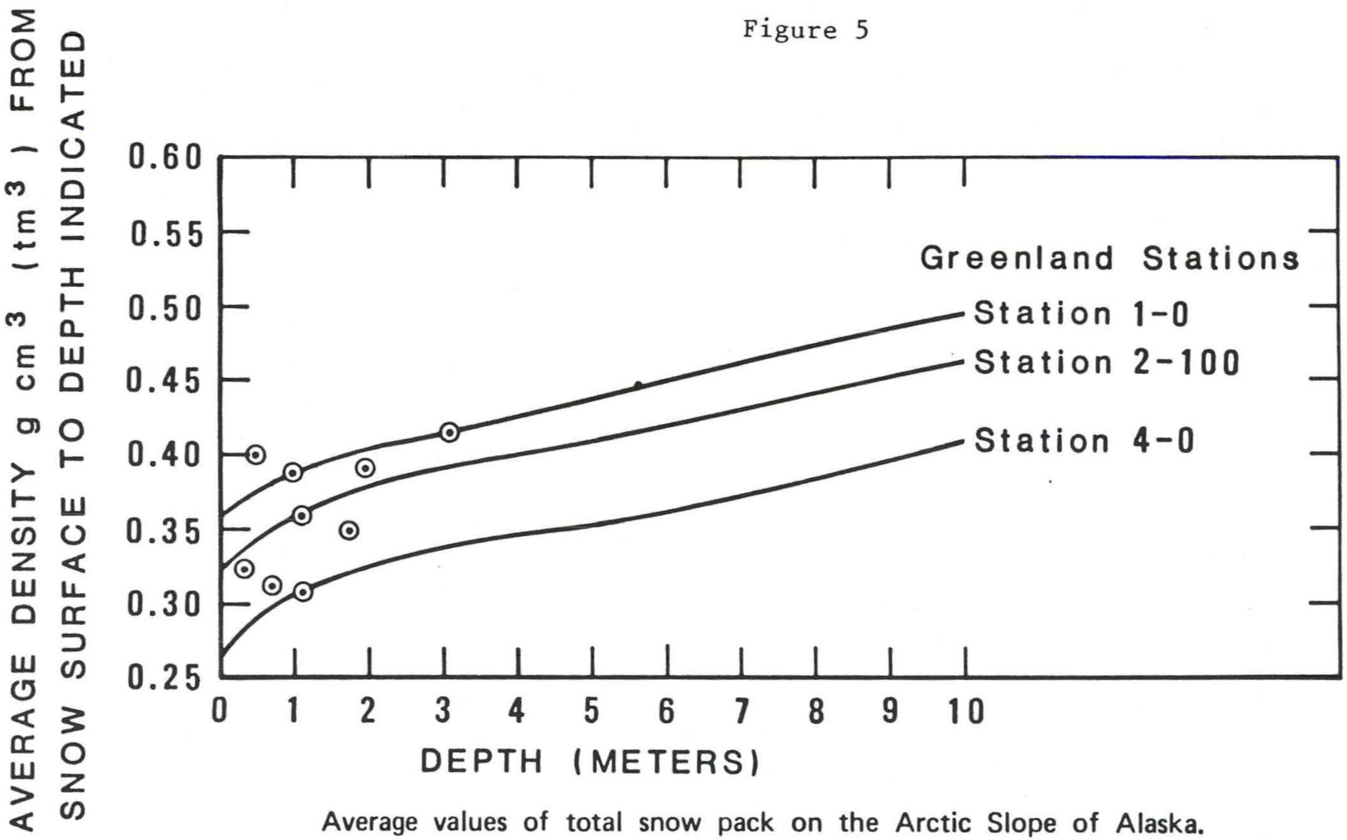
TABLE 11

Summary of Snow Drifts, from East and West winds, at Atkasook, Meade River, Alaska (see Figure 1)

Drift from East Winds			Drift from West Winds		
Year	Cross sectional area (m^2), extending 50 m from edge of bank	Mass ($t\ m^{-1}$) extending 50 m from edge of bank	Cross sectional area (m^2) extending 50 m from edge of bank	Mass ($t\ m^{-1}$) extending 50 m from edge of bank	
1962	I --	--	I 99 ± 3	40 ± 1.0	
1962	II --	--	II 94	* 37	
1963	192 ± 7	80 ± 3.0	98 ± 3	38 ± 1.0	
1964	166 ± 5	68 ± 2.0	A 60 ± 1	21 ± 0.5	
1964			B 49	* 17	
1965	161 ± 4	67 ± 1.6	96 ± 3	38 ± 1.2	
1966	144 ± 6	57 ± 2.3	84 ± 2	34 ± 0.7	
1967	127 ± 5	50 ± 2.0	154 ± 4	63 ± 1.7	
1968	--	--	--	--	
1969	--	--	--	--	
1970	280 ± 5	125 ± 2.2	78 ± 1	29 ± 0.4	
1971	--	--	--	--	
1972	--	--	--	--	
1973	137 ± 3	56 ± 1.1	80 ± 1.5	30 ± 0.6	
1974	--	--	--	--	
1975	(a) 182 ± 5	77 ± 2	66 ± 1	24 ± 0.5	
1975	(b) 159	* 65 **	--	--	
1976	--	--	55 ± 1	* 19 ± 0.5	16 April 1976
1976	116 ± 4	44 ± 1.5	64 ± 1	22 ± 0.5	28 April 1976
1977	267 ± 5	114 ± 2.1	63 ± 1	22 ± 0.5	
1978	167 ± 4	70 ± 1.6	64 ± 1	23 ± 0.5	
1979	131 ± 3	52 ± 1.1	46 ± 1	16 ± 0.5	
	range 44 to 125 $t\ m^{-1}$; 12 entries $\bar{x}$ = 72, s = 25	*not used in average; ** see text	range 16 to 63 $t\ m^{-1}$; 13 entries $\bar{x}$ = 31, s = 12	*not used in average	

Figure 5



Average values of total snow pack on the Arctic Slope of Alaska. The curves indicate the AVERAGE DENSITY VALUE from the snow surface to the indicated depth. They do NOT indicate depth vs. density as usually diagrammed.

Measured snow profiles on the Arctic Slope include cases up to 3.2 m deep. A relation between snow pack depth and average density of the pack was determined for use at Prudhoe Bay (Benson et al., 1975). However, the drifts encountered on the Meade River are deeper (over 10 m) so the problem was re-examined. The three smooth curves in Figure 5 show the average snow density from the snow surface to depths of 10 m for three sites along a spectrum of increasing melt action on the Greenland Ice Sheet (Benson, 1962); the data points are from the Alaskan Arctic Slope. Although there is considerable variability in the shallow (less than 1 m) snow packs, the curve 2-100 gives a reasonable estimate for deeper depths, and was used in these calculations. This is essentially an extension of the relationship used for the top 3 m at Prudhoe Bay (Benson et al., 1975, p. 29). A summary of the numerical values follows:

Depth Range (m)	Average Density ($t\ m^{-3}$, or $g\ cm^{-3}$)
0-1	0.36
0-2	0.38
0-3	0.39
0-4	0.40
0-5	0.41
0-6	0.42
0-7	0.43
0-8	0.44
0-9	0.45
0-10	0.46

The errors were estimated according to the uncertainty of depth determinations and surface slope measurements. The mass is expressed in metric tons of snow in a 1 m width perpendicular to the wind, and extending 50 m from the top of the bank.

Considerable variability exists in the drifts from year to year but the prevailing east winds clearly move more snow than do the

west winds by a factor of two. This agrees with the measurements on snow fences at Barrow reported by Slaughter et al. (1975).

In summary the annual flux of blowing snow on the western part of the Arctic Slope is 72 t m^{-1} from the east with a range of 44 to 125 t m^{-1} and from the west it is 31 t m^{-1} with a range of 16 to 63 t m^{-1}.

Estimates of the Transport Distance

Theoretical studies on the transport of blowing snow by Schmidt (1972), Tabler and Schmidt (1973) and Tabler (1965) have introduced some simplifications in to the complex problem, which are useful here. In particular we shall follow Tabler's (1975, 1976a) approach to define the flux, Q,

$$Q = \frac{P_r R_\mu}{2} \left(1-(0.14)^{R_c/R_\mu}\right) \qquad (1)$$

for a single wind direction.

where Q is the flux (t m^{-1}) as defined above

P_r = the relocated snow (mm H_2O)

R_μ = the transport distance (m), and

R_c = the distance of Fetch (m).

The transport distance, R_μ, is defined as the distance which the average sized snow particle will travel before it completely sublimes. On the Arctic Slope we can set $R_c = \infty$. This simplifies Eq. (1) since the term $(0.14)^{R_c/R_\mu}$ vanishes. However, we have two primary wind directions, so a flux can be calculated for each of them as follows:

$$Q_\alpha = \frac{f_\alpha P_r R_\mu}{2}$$

f_α is the frequency of wind from direction, α. In our case, two values of f_α will suffice: one for the east wind $f_E = 2/3$ and one from the west wind $f_W = 1/3$.

To obtain order of magnitude values of the transport distance R_μ, based on our corrected average snow precipitation data from Barrow, P, the average snow on the tundra P_t and using the average values of snow in drift traps at Meade River Q_d, and neglecting Q_e, we obtain the following long term average values,

$P = 195$ mm H_2O (snow only)

$P_t = 113$ mm H_2O

$P_r = P-P_T \approx 82$ mm H_2O

$Q_d \approx 72$ t m^{-1} from east winds

$Q_d \approx 31$ t m^{-1} from west winds

We can express the transport distance as

$$R_\mu = \frac{2\ Q_d}{f_\alpha P_r}$$

Using the above values we obtain

R_μ (east) ≈ 2634 m

R_μ (west) ≈ 2268 m

These values are less than the average value of 3000 m determined by Tabler (1975) for Wyoming.

Tabler (1976b) estimated that the higher wind speed at Barter Island, an average of 1.17 times that at Barrow, would result in a larger transport distance there than at Barrow--and even a higher value than the one he derived for Wyoming. Perhaps more significant than the average wind, is the speed

of the fastest mile. Between 1962 and 1969 Barter Islands average fastest mile was 29 meters per seconnd (65 miles per hour) which exceeds the Barrow average by a factor of 1.56.

It is important to stress the fact that the transport distances calculated for the Arctic Slope were based on average values. The values for 1969-70 are greater: R_μ (east) = 10.7 km, R_μ (west) = 5.0 km. The 1969-70 year was anomalous in that it had less than the normal amount of precipitation (Table 6) but the largest of all drifts from east winds. The east winds must have been especially effective in moving snow from the east during the 1969-70 winter. The exceptionally small drift from west winds, and its lack of a cornice may mean that it was eroded by the effective west winds.

The average correction factor of 3 for the winter snow record is obviously too high for years with winters with heavy snowfall such as 1962-63 and 1972-73. If the average correction factor is applied to these years one would obtain impossible results--namely negative values for P_r. If the correction factor is reduced to 1/2 of its average value for these years the transport distances are: 1962-63, R_μ = 3530 (east winds) and 3350 (west winds); 1972-73, R_μ = 3650 (east winds) and 3900 (west winds).

Clearly, more detailed information is needed on the problems of wind blown snow on the Arctic Slope. But the approach to these problems which has been developed in Wyoming appears promising. Because of the lower temperatures on the Arctic Slope, we expect larger transport distances (Schmidt, 1972). Our data indicate that this is clearly the case for some years in the western part of the Arctic Slope and perhaps for all years in the eastern part.

CONCLUSIONS AND RECOMMENDATIONS

It has been established that the precipitation in the form of snow is considerably higher than recorded by the unshielded gauges used by the Weather Service on the Arctic Slope. Average correction factors have been determined for the winter snow precipitation, and for the summer rain precipitation. The correction for an individual year may vary considerably from the averages. The amount of snow remaining on the tundra after wind action, and the amounts relocated by the two primary winds have been measured. Order of magnitude values for these parameters exist but it is necessary to establish a systematic program of improved measurements on these parameters.

To a large extent the value of this work has been to define the problems and to establish some limits on the parameters.

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